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APOLLO 10 TRANSEARTH COMMUNICATION LOSS PROCEDURES

MATHEMATICAL PHYSICS BRANCH
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MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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PROJECT APOLLO

APOLLO 10 TRANSEARTH COMMUNICATION LOSS PROCEDURES

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TRW Systems Group

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MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
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CONTENTS

TABLES

FIGURES

APOLLO 10 TRANSEARTH COMMUNICATION LOSS PROCEDURES

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1. INTRODUCTION AND SUMMARY

In the event of a communication loss with the earth, the CSM would have to use the onboard spacecraft estimate of state to target midcourse corrections. To insure safe reentry the 3-sigma flight-path angle (β) uncertainty for a fixed reentry radius must be less than 0.5 degree at the time of the last midcourse correction. For automatic reentry guidance the 3-sigma altitude rate error ($\dot{U}$) at nominal reentry time should be less than 200 feet per second (otherwise the manual system may be required). The onboard estimate of state (derived from an estimate originally computed in the RTCC from MSFN tracking) may be updated by processing sextant data marks. The sextant data types considered for this purpose are the included angle (trunnion angle) measurements between a star direction and the corresponding near or far horizon substellar point (Figure 1). This document presents contingency navigation procedures for use in the event of communication loss on the nominal transearth trajectory. The basic idea is to establish an acceptable sighting schedule, consisting of groupings or batches of sextant sightings from TEI to reentry, to be used in the event of communication loss. In the event of a communication loss, the sighting schedule would begin with the first mark of the next complete batch of optical sightings following the time of the loss. The schedule is to be followed from the initial batch after the loss to the last recommended batch.

The navigation schedule presented here is designed for the transearth portion of the Apollo 10 mission which assumes a 72-degree launch azimuth on May 18 with a first opportunity TLI (hereafter denoted May 18 trajectory). The schedule is consistent with mission constraints such as astronaut rest cycles, horizon lighting, sextant hardware limitations, passive thermal control, and star availability. These are considered in more detail later.

The specific results generated for Apollo 10 using the communication loss techniques presented in this document have been fully integrated into the flight plan and ground and onboard procedures. This report is written to document the analysis which leads to the development of these techniques.

The following is a summary of important results:

1. A sighting schedule for Apollo 10 to be used with initial weighting matrix values of (3300 feet)^2 in each position component and (3.3 feet per second)^2 in each velocity component has been determined. The a priori covariance matrix (denoted by WW^T) is used to "weight in" the initial estimate of state at the first mark time and is constrained to be a diagonal matrix with three equal position weights and three equal velocity weights. The two-position and velocity parameters are determined premission and are stored in the computer erasable memory.

2. A fixed W-matrix of 3300 feet and 3.3 feet per second for use in all communication loss situations will not suffice.

3. The schedule will yield acceptable reentry accuracies for all possible communication loss cases if the recommended W-matrix values are used at the first mark time. (Specific W-matrix values to be used for an Apollo 10, May 18 launch are presented.)

4. An average W-matrix for a large class of communication loss cases is as good as the specific W-matrix values determined from propagated MSFN covariance matrices.

5. Ideally, sightings should be stopped early for certain communication loss cases. However, because of venting, water dumping, and possibly other effects which may alter spacecraft trajectory, it is advised that all remaining sightings be taken.

6. A procedure to be followed in the event of accidental loss of W-matrix, after having initialized optical tracking, may be determined from results of communication loss analysis.

7. There are communication loss times when it is recommended that optical tracking not be initiated to improve the onboard estimate of state.

2. SYMBOLS

CSM	command and service module
MCC	midcourse correction
MSFN	Manned Space Flight Network
RTCC	Real-Time Computer Complex
TEI	transearth injection
TLI	translunar injection
$\dot{U}$	radial velocity
W	square root of the filter (or fit-world) a priori estimate covariance matrix, Λ i.e., $WW^T = \Lambda$
β	flight-path angle

3. APPROACH

The results contained in this report are based on a linear error analysis.* This assumes that the significant errors are sufficiently small to cause linear deviations from a nominal reference trajectory. The analysis considers errors in the sextant trunnion angle, in the observed horizon altitude for both the earth and the moon, and in the gravitational constants for both the earth and the moon. The analysis neglects time errors, errors in the onboard approximation of the lunar ephemeris, and errors in the onboard trajectory integration.

The particular error model used in this analysis is given in the following table. The numbers given are 1-sigma values.

Error	Error Model (1σ) Noise	Bias
Sextant trunnion angle	11.5 sec	5.0 sec
Earth horizon altitude	2.2 km	3.0 km
Lunar horizon altitude	1.5 km	2/3 km
Earth gravitational constant	0	1.6×10^{11} ft^3/sec^2
Lunar gravitational constant	0	7.1×10^{9} ft^3/sec^2

The objective of this error analysis was to develop a procedure to follow in case of a communication loss between earth and the CSM. The procedure should tell what optical tracking data to take and what initial W-matrix to use at the time of the first observation. For simplicity a fixed schedule of optical tracking is desired so that tracking may begin with the first series of sightings scheduled after the communication loss occurs. The schedule is to extend from TEI to reentry. The W-matrix is a matrix used by the onboard computer to weigh in the initial state estimate. (WW^T is the "fit-world a priori" covariance matrix.) It is restricted (initially) to be a 6 x 6 diagonal matrix in which $w_{11} = w_{22} = W_{33}$ and $w_{44} = w_{55} = w_{66}$.

Tracking consists of observations of the angle between a star and either the near or far horizon of the earth or moon measured with a sextant. There are several constraints to be taken into consideration in making out an observation schedule. Some, such as illumination of horizons, minimum and maximum sextant trunnion angles, star magnitude,

*The TAPP-IV, FASTAP, and SNAP programs were used. See References 1, 2, and 3.

and the angle between a star and the sun determine the star/horizon combinations available. Others, such as rest cycles, midcourse correction times, and passive thermal control determine the times at which sightings may be taken.

When all available star/horizon combinations are known, the sighting schedule may be constructed. In making out a sighting schedule it must be decided for each series of sightings whether to use the earth or moon as the horizon body. Next, it must be decided which stars to use and how many sightings to take with each one. The choice of star/horizon combinations depends on the distance from the earth or moon, which errors it is desired to correct, and whether a star is near the orbit plane or far out of the orbit plane. The manner in which errors propagate is also taken into consideration.* The sighting schedule chosen for the F mission, May 18 trajectory is given in Table I.

The initial value of the W-matrix also has a significant effect on navigational accuracy. The optimal value of W depends largely on the covariance matrix of the MSFN state estimate at the time of the communication loss. The following method was used to obtain acceptable initial values of W to be used with the various series of sightings. The covariance matrix of the last MSFN update was propagated to the first observation in each batch. Then W was chosen so that the position and velocity root-semitraces of WW^T would be the same as for the propagated MSFN covariance matrix. Since this would result in a different W for each series of sightings, a weighted average was taken over several series. This worked satisfactorily, as will be shown later, and resulted in only a few different values for W.

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*See Reference 4 for detailed guidelines.

4. RESULTS

All times between TEI and reentry were considered as possible communication loss times. MSFN updates were assumed to occur at 10, 15, 25, and 35 hours from TEI. The MSFN update at TEI + 35 hours yields such small reentry uncertainties that it is not advantageous to take optical data after this update has been received. If a communication loss occurs between TEI and this update, optical tracking begins with the first batch of sightings from the full schedule beginning after the loss, and the MSFN update which is onboard is used as a priori for the optical tracking. The full sighting schedule for the Apollo 72-degree, May 18 launch trajectory is given in Table I. The reentry accuracies achieved using this schedule are given in Figures 2 and 3. Poor accuracies are caused by a lack of stars close to the orbit plane.

In three of the communication loss situations, a W-matrix with values of 3300 feet and 3.3 feet per second was used at the first mark time. The reentry accuracies obtained using this fixed W-matrix are given in Table II. The reentry flight-path angle uncertainty at the time of the last MCC is critical. In the last two communication loss situations in Table II, the flight-path angle uncertainty is unacceptable at that time. When these large uncertainties were discovered, an attempt was made to improve the reentry results by using a different W-matrix.

W-matrices with position and velocity root semitraces of the same order as those of the MSFN covariance matrix at the time of the first mark were used. (These are denoted as variable W's.) With the use of these W-matrices which depend upon the communication loss situation, the reentry results were significantly improved. The W-matrix used in each situation and the reentry accuracies obtained are given in Table III. Although the results are much better, the procedure is more complicated. To simplify the procedure, the expected value of the variable W-matrix for loss times between TEI + 10 hours and TEI + 36 hours was tried. This average W-matrix, W_A, was calculated as follows:

$$W_A = \sum_{i=1}^{n} \frac{\Delta t_i}{t} W_i$$

where $W_1, \ldots, W_n$ are the variable W-matrices which would be used if a communication loss occurred during the time intervals $\Delta t_1, \ldots, \Delta t_n$, respectively and

$$t = \sum_{i=1}^{n} \Delta t_i .$$

The results obtained using this average W-matrix are also given in Table III. The results using the variable W-matrix and the average W-matrix are very similar in all cases. The large radial velocity errors seen in both cases could require that the manual reentry system be used.

The use of one W-matrix for many loss situations has several advantages. One advantage is that it is a much simpler procedure to follow. Another is that it gives a procedure to follow if MSFN updates come at times other than those for which the variable W-matrices are tailored.

The results obtained after the incorporation of the optical data are not significantly better than those obtained from the MSFN update alone. Taking this optical data becomes important if execution errors for the MCC's are considered. Table IV gives the reentry uncertainties for one communications loss case with and without execution errors of 0.2 feet per second in each local U, V, W direction at MCC-5.* The onboard accuracy of the β estimate is not acceptable when execution errors are considered. When optical data is taken, accuracies at the time of the last MCC are almost the same with and without degrading. This justifies taking the optical data.

Another possible problem is the accidental loss of the W-matrix after some sightings have been taken. If this occurs before the next MSFN update would have occurred were communications not lost, acceptable reentry accuracies can be achieved by using the stored MSFN update as a priori knowledge and proceeding as if the communication loss had just occurred. If the W-matrix is lost after the next MSFN update would have occurred, using the average W-matrix at the first mark of the next batch of data in conjunction with the current estimate is a possible procedure. For example, if the MSFN update being used as a priori knowledge is the one received at TEI + 15 hours, and if the W-matrix is lost before TEI + 25 hours, the optical data taken before the loss should be ignored and the stored MSFN update should be used as a priori knowledge. In a similar case, if the W-matrix is lost more than 25 hours after TEI, the current estimate should be used as a priori knowledge. In both cases, the average W-matrix is used at the first mark in the first batch of sightings following the W-matrix loss, and the remaining optical sightings are taken. The results of four cases following this procedure are given in Table V. In three cases the results are acceptable. In these three cases the $\dot{U}$ error could require that the manual reentry system be used.

Final reentry flight-path angle and radial velocity uncertainties as a function of the communication loss time are given in Figures 4 and 5. These figures summarize the expected reentry accuracies for the situations in Table II showing the accuracies achieved using each of the a priori weighting matrix (W) schemes considered and using the MSFN updates only.

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*U is positive radially outward, W is positive in the direction of the angular momentum vector, and V completes the right handed system.

5. CONCLUSIONS AND RECOMMENDATIONS

The recommended procedures in case of a communication loss are summarized in Table VI. No optical tracking should be performed if the MSFN update at TEI + 35 hours is received. The average W-matrix should be used for all communication loss times between TEI + 10 hours and TEI + 35 hours. If the communication loss occurs between TEI + 25 hours and TEI + 35 hours, better reentry results are obtained by taking only the first batch of sightings beginning after the loss. (The information gained by taking more sightings is not enough to compensate for the effect of the earth horizon bias, see results in Table III.) However, this cannot be recommended as a result of water dump, venting, and possibly other effects which may alter the trajectory.

In case of an accidental loss of the W-matrix after sightings have been taken, the recommended procedure is to maintain the current state and use the average W-matrix at the first mark of the next set of sightings if the loss occurs any time after the next MSFN update would have occurred. If the loss occurs earlier, use the stored MSFN updated state as a priori knowledge and proceed as if the communication loss had just occurred.

Table I. Full Transearth Sighting Schedule - F Mission, May 18 (Reference 5)

Time from TEI for Beginning of Batch (hr)	Central Body	Star Horizon Combination
1.5	Moon	25 Far
		18 Near
		18 Near
		17 Near
		17 Near
12.5	Moon	18 Near
		18 Near
		20 Far
		22 Far
		22 Far
13.5	Earth	1 Near
		1 Near
		2 Near
16	Earth	32 Far
		2 Near
		2 Near
		1 Near
		1 Near
20	Moon	18 Near
		22 Far
		22 Far
23	Earth	1 Near
		1 Near
		32 Far
26	Earth	2 Near
		2 Near
		1 Near
		1 Near
36	Earth	36 Far
		1 Near
		1 Near
37	Moon	18 Near
		22 Far
		22 Far

Table I. Full Transearth Sighting Schedule - F Mission, May 18, (Continued)

Time from TEI for Beginning of Batch (hr)	Central Body	Star Horizon Combination
38. 5	Earth	36 Far
		2 Near
		2 Near
		1 Near
		1 Near
43	Moon	25 Far
		22 Far
		22 Far
44	Earth	36 Far
		1 Near
		1 Near
		2 Near
		2 Near
46. 5	Earth	1 Near
		1 Near
		37 Far
49. 5	Earth	1 Near
		37 Far
52	Earth	36 Far
		37 Far
		37 Far

Table II. Communication Loss - with W-Matrix = 3300/3.3

Situation 1

Communication Loss Occurs - TEI - TEI + 1.5 hr
MSFN Update - TEI
First Data from Schedule Used - 1st Batch

Data Incorporated		Fixed W (3300/3.3)
MSFN Update (TEI)	β (1σ) deg	4.80
	$\dot{U}$ (1σ) ft/sec	2681
1st Batch (TEI + 1.5)	β	7.25
	$\dot{U}$	4181
2nd Batch (TEI + 12.5)	β	2.38
	$\dot{U}$	5149
3rd Batch (TEI + 13.5)	β	0.785
	$\dot{U}$	1640
4th Batch (TEI + 16)	β	0.455
	$\dot{U}$	963
5th Batch (TEI + 20)	β	0.454
	$\dot{U}$	925
6th Batch (TEI + 23)	β	0.281
	$\dot{U}$	617
7th Batch (TEI + 26)	β	0.250
	$\dot{U}$	565
8th Batch (TEI + 36)	β	0.187
	$\dot{U}$	529
9th Batch (TEI + 37)	β	0.187
	$\dot{U}$	441
10th Batch (TEI + 38.5)	β	0.165
	$\dot{U}$	418
11th Batch (TEI + 43)	β	0.165
	$\dot{U}$	380
12th Batch (TEI + 44)	β	0.163
	$\dot{U}$	393
13th Batch (TEI + 46.5)	β	0.165
	$\dot{U}$	397
14th Batch (TEI + 49.5)	β	0.156
	$\dot{U}$	312
15th Batch (TEI + 52)	β	0.106
	$\dot{U}$	137

Table II. Communication Loss - with W-Matrix = 3300/3.3 (Continued)

Situation 2

Communication Loss Occurs - TEI + 1.5 - TEI + 10
MSFN Update - TEI
First Data from Schedule Used - 2nd Batch

Data Incorporated		Fixed W (3300/3.3)
MSFN Update (TEI)	β (1σ) deg $\dot{U}$ (1σ) ft/sec	4.80 2681
2nd Batch (TEI + 12.5)	β $\dot{U}$	43.6 5325
3rd Batch (TEI + 13.5)	β $\dot{U}$	40.6 7240
4th Batch (TEI + 16)	β $\dot{U}$	15.7 26285
5th Batch (TEI + 20)	β $\dot{U}$	6.96 5907
6th Batch (TEI + 23)	β $\dot{U}$	3.49 2444
7th Batch (TEI + 26)	β $\dot{U}$	2.22 3677
8th Batch (TEI + 36)	β $\dot{U}$	1.05 5217
9th Batch (TEI + 37)	β $\dot{U}$	1.42 1049
10th Batch (TEI + 38.5)	β $\dot{U}$	0.754 1329
11th Batch (TEI + 43)	β $\dot{U}$	0.868 685
12th Batch (TEI + 44)	β $\dot{U}$	0.569 835
13th Batch (TEI + 46.5)	β $\dot{U}$	0.559 752
14th Batch (TEI + 49.5)	β $\dot{U}$	0.736 898
15th Batch (TEI + 52)	β $\dot{U}$	0.670 463

Table II. Communication Loss - with W-Matrix = 3300/3.3 (Continued)

Situation 3

Communication Loss Occurs - TEI + 20 - TEI + 23
MSFN Update - TEI + 15
First Data from Schedule Used - 6th Batch

Data Incorporated		Fixed W (3300/3.3)
MSFN Update (TEI + 15)	β (1σ) deg $\dot{U}$ (1σ) ft/sec	0.166 79.3
6th Batch (TEI + 23)	β $\dot{U}$	0.321 112
7th Batch (TEI + 26)	β $\dot{U}$	1.49 508
8th Batch (TEI + 36)	β $\dot{U}$	0.375 625
9th Batch (TEI + 37)	β $\dot{U}$	0.390 656
10th Batch (TEI + 38.5)	β $\dot{U}$	0.295 547
11th Batch (TEI + 43)	β $\dot{U}$	0.296 522
12th Batch (TEI + 44)	β $\dot{U}$	0.260 510
13th Batch (TEI + 46.5)	β $\dot{U}$	0.266 557
14th Batch (TEI + 49.5)	β $\dot{U}$	0.237 458
15th Batch (TEI + 52)	β $\dot{U}$	0.139 156

Table III. Communication Loss - with Variable W and Average W

Situation 1

Communication Loss Occurs - TEI + 1.5 - TEI + 10
MSFN Update - TEI
First Data from Schedule Used - 2nd Batch

Data Incorporated		Variable W (73,346/4.927)
MSFN Update (TEI)	β (1σ) deg	4.80
	$\dot{U}$ (1σ) ft/sec	2681
2nd Batch (TEI + 12.5)	β	3.32
	$\dot{U}$	2672
3rd Batch (TEI + 13.5)	β	2.82
	$\dot{U}$	1505
4th Batch (TEI + 16)	β	2.04
	$\dot{U}$	2193
5th Batch (TEI + 20)	β	1.29
	$\dot{U}$	2285
6th Batch (TEI + 23)	β	0.601
	$\dot{U}$	1063
7th Batch (TEI + 26)	β	0.514
	$\dot{U}$	938
8th Batch (TEI + 36)	β	0.282
	$\dot{U}$	660
9th Batch (TEI + 37)	β	0.279
	$\dot{U}$	525
10th Batch (TEI + 38.5)	β	0.216
	$\dot{U}$	439
11th Batch (TEI + 43)	β	0.215
	$\dot{U}$	421
12th Batch (TEI + 44)	β	0.199
	$\dot{U}$	417
13th Batch (TEI + 46.5)	β	0.202
	$\dot{U}$	441
14th Batch (TEI + 49.5)	β	0.176
	$\dot{U}$	334
15th Batch (TEI + 52)	β	0.100
	$\dot{U}$	130

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 2

Communication Loss Occurs - TEI + 10 - TEI + 12.5
MSFN Update - TEI + 10
First Data from Schedule Used - 2nd Batch

Data Incorporated		Variable W (25,100/0.795)	Average W (30,100/0.465)
MSFN Update	β (1σ) deg	0.152	0.152
(TEI + 10)	$\dot{U}$ (1σ) ft/sec	65.9	65.9
2nd Batch	β	0.180	0.135
(TEI + 12.5)	$\dot{U}$	59.9	58.7
3rd Batch	β	0.220	0.156
(TEI + 13.5)	$\dot{U}$	175	173
4th Batch	β	0.374	0.198
(TEI + 16)	$\dot{U}$	244	198
5th Batch	β	0.225	0.170
(TEI + 20)	$\dot{U}$	294	208
6th Batch	β	0.207	0.157
(TEI + 23)	$\dot{U}$	297	193
7th Batch	β	0.271	0.202
(TEI + 26)	$\dot{U}$	414	257
8th Batch	β	0.180	0.150
(TEI + 36)	$\dot{U}$	358	235
9th Batch	β	0.177	0.134
(TEI + 37)	$\dot{U}$	340	242
10th Batch	β	0.171	0.142
(TEI + 38.5)	$\dot{U}$	342	262
11th Batch	β	0.172	0.142
(TEI + 43)	$\dot{U}$	340	269
12th Batch	β	0.168	0.142
(TEI + 44)	$\dot{U}$	347	278
13th Batch	β	0.170	0.142
(TEI + 46.5)	$\dot{U}$	370	297
14th Batch	β	0.158	0.139
(TEI + 49.5)	$\dot{U}$	303	265
15th Batch	β	0.099	0.095
(TEI + 52)	$\dot{U}$	131	129

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 3

Communication Loss Occurs - TEI + 12.5 - TEI + 13.5
MSFN Update - TEI + 10
First Data from Schedule Used - 3rd Batch

Data Incorporated		Variable W (27,700/0.793)	Average W (30,100/0.465)
MSFN Update	β (1σ) deg	0.152	0.152
(TEI + 10)	$\dot{U}$ (1σ) ft/sec	65.9	65.9
3rd Batch	β	0.157	0.154
(TEI + 13.5)	$\dot{U}$	83.6	82.5
4th Batch	β	0.286	0.169
(TEI + 16)	$\dot{U}$	135	92.9
5th Batch	β	0.215	0.117
(TEI + 20)	$\dot{U}$	236	179
6th Batch	β	0.304	0.171
(TEI + 23)	$\dot{U}$	274	179
7th Batch	β	0.376	0.264
(TEI + 26)	$\dot{U}$	355	243
8th Batch	β	0.208	0.180
(TEI + 36)	$\dot{U}$	321	218
9th Batch	β	0.189	0.150
(TEI + 37)	$\dot{U}$	335	238
10th Batch	β	0.177	0.152
(TEI + 38.5)	$\dot{U}$	337	256
11th Batch	β	0.178	0.152
(TEI + 43)	$\dot{U}$	339	266
12th Batch	β	0.170	0.147
(TEI + 44)	$\dot{U}$	345	274
13th Batch	β	0.171	0.144
(TEI + 46.5)	$\dot{U}$	366	291
14th Batch	β	0.159	0.142
(TEI + 49.5)	$\dot{U}$	296	258
15th Batch	β	0.103	0.100
(TEI + 52)	$\dot{U}$	132	129

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 4

Communication Loss Occurs - TEI + 13.5 - TEI + 15
MSFN Update - TEI + 10
First Data from Schedule Used - 4th Batch

Data Incorporated		Variable W (34,400/0.788)	Average W (30,100/0.465)
MSFN Update	β (1σ) deg	0.152	0.152
(TEI + 10)	$\dot{U}$ (1σ) ft/sec	65.9	65.9
4th Batch	β	0.154	0.150
(TEI + 16)	$\dot{U}$	87.6	83.8
5th Batch	β	0.123	0.095
(TEI + 20)	$\dot{U}$	175	153
6th Batch	β	0.298	0.148
(TEI + 23)	$\dot{U}$	221	155
7th Batch	β	0.411	0.261
(TEI + 26)	$\dot{U}$	296	218
8th Batch	β	0.214	0.181
(TEI + 36)	$\dot{U}$	269	195
9th Batch	β	0.186	0.146
(TEI + 37)	$\dot{U}$	318	224
10th Batch	β	0.181	0.153
(TEI + 38.5)	$\dot{U}$	330	245
11th Batch	β	0.182	0.152
(TEI + 43)	$\dot{U}$	336	258
12th Batch	β	0.173	0.147
(TEI + 44)	$\dot{U}$	342	266
13th Batch	β	0.172	0.143
(TEI + 46.5)	$\dot{U}$	363	283
14th Batch	β	0.162	0.142
(TEI + 49.5)	$\dot{U}$	296	254
15th Batch	β	0.104	0.102
(TEI + 52)	$\dot{U}$	132	130

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 5

Communication Loss Occurs - TEI + 15 - TEI + 16
MSFN Update - TEI + 15
First Data from Schedule Used - 4th Batch

Data Incorporated		Variable W (25,400/0.543)	Average W (30,100/0.465)
MSFN Update	β (1σ) deg	0.166	0.166
(TEI + 15)	$\dot{U}$ (1σ) ft/sec	79.3	79.3
4th Batch	β	0.161	0.161
(TEI + 16)	$\dot{U}$	76.8	77.0
5th Batch	β	0.130	0.126
(TEI + 20)	$\dot{U}$	144	165
6th Batch	β	0.190	0.165
(TEI + 23)	$\dot{U}$	167	165
7th Batch	β	0.302	0.264
(TEI + 26)	$\dot{U}$	232	217
8th Batch	β	0.190	0.179
(TEI + 36)	$\dot{U}$	203	192
9th Batch	β	0.157	0.147
(TEI + 37)	$\dot{U}$	248	225
10th Batch	β	0.162	0.154
(TEI + 38.5)	$\dot{U}$	269	245
11th Batch	β	0.162	0.153
(TEI + 43)	$\dot{U}$	283	259
12th Batch	β	0.156	0.148
(TEI + 44)	$\dot{U}$	290	266
13th Batch	β	0.153	0.143
(TEI + 46.5)	$\dot{U}$	309	283
14th Batch	β	0.150	0.142
(TEI + 49.5)	$\dot{U}$	270	254
15th Batch	β	0.103	0.102
(TEI + 52)	$\dot{U}$	132	130

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 6

Communication Loss Occurs - TEI + 16 - TEI + 20
MSFN Update - TEI + 15
First Data from Schedule Used - 5th Batch

Data Incorporated		Variable W (29,200/0.537)	Average W (30,100/0.465)
MSFN Update (TEI + 15)	β (1σ) deg	0.166	0.166
	$\dot{U}$ (1σ) ft/sec	79.3	79.3
5th Batch (TEI + 20)	β	0.139	0.139
	$\dot{U}$	92.1	92.1
6th Batch (TEI + 23)	β	0.151	0.144
	$\dot{U}$	129	127
7th Batch (TEI + 26)	β	0.263	0.226
	$\dot{U}$	183	177
8th Batch (TEI + 36)	β	0.181	0.171
	$\dot{U}$	155	152
9th Batch (TEI + 37)	β	0.142	0.136
	$\dot{U}$	214	199
10th Batch (TEI + 38.5)	β	0.161	0.152
	$\dot{U}$	246	224
11th Batch (TEI + 43)	β	0.160	0.150
	$\dot{U}$	263	241
12th Batch (TEI + 44)	β	0.155	0.146
	$\dot{U}$	272	250
13th Batch (TEI + 46.5)	β	0.151	0.141
	$\dot{U}$	290	266
14th Batch (TEI + 49.5)	β	0.149	0.141
	$\dot{U}$	259	244
15th Batch (TEI + 52)	β	0.106	0.104
	$\dot{U}$	133	132

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 7

Communication Loss Occurs - TEI + 20 - TEI + 23
MSFN Update - TEI + 15
First Data from Schedule Used - 6th Batch

Data Incorporated		Variable W (34,600/0.53)	Average W (30,100/0.465)
MSFN Update	β (1σ) deg	0.166	0.166
(TEI + 15)	$\dot{U}$ (1σ) ft/sec	79.3	79.3
6th Batch	β	0.140	0.141
(TEI + 23)	$\dot{U}$	68.3	68.9
7th Batch	β	0.188	0.172
(TEI + 26)	$\dot{U}$	77.0	73.3
8th Batch	β	0.175	0.161
(TEI + 36)	$\dot{U}$	63.7	62.5
9th Batch	β	0.147	0.133
(TEI + 37)	$\dot{U}$	183	162
10th Batch	β	0.194	0.177
(TEI + 38.5)	$\dot{U}$	238	211
11th Batch	β	0.190	0.172
(TEI + 43)	$\dot{U}$	257	230
12th Batch	β	0.178	0.165
(TEI + 44)	$\dot{U}$	266	240
13th Batch	β	0.165	0.153
(TEI + 46.5)	$\dot{U}$	282	255
14th Batch	β	0.166	0.155
(TEI + 49.5)	$\dot{U}$	260	242
15th Batch	β	0.117	0.113
(TEI + 52)	$\dot{U}$	134	132

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 8

Communication Loss Occurs - TEI + 23 - TEI + 25
MSFN Update - TEI + 15
First Data from Schedule Used - 7th Batch

Data Incorporated		Variable W (39,900/0.521)	Average W (30,100/0.465)
MSFN Update	β (1σ) deg	0.166	0.166
(TEI + 15)	$\dot{U}$ (1σ) ft/sec	79.3	79.3
7th Batch	β	0.151	0.149
(TEI + 26)	$\dot{U}$	71.0	70.5
8th Batch	β	0.176	0.162
(TEI + 36	$\dot{U}$	60.8	61.9
9th Batch	β	0.158	0.141
(TEI + 37)	$\dot{U}$	172	143
10th Batch	β	0.211	0.186
(TEI + 38.5)	$\dot{U}$	227	190
11th Batch	β	0.203	0.178
(TEI + 43)	$\dot{U}$	243	208
12th Batch	β	0.184	0.168
(TEI + 44)	$\dot{U}$	254	220
13th Batch	β	0.165	0.148
(TEI + 46.5)	$\dot{U}$	268	233
14th Batch	β	0.167	0.151
(TEI + 49.5)	$\dot{U}$	251	226
15th Batch	β	0.123	0.117
(TEI + 52)	$\dot{U}$	133	131

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 9

Communication Loss Occurs - TEI + 25 - TEI + 26
MSFN Update - TEI + 25
First Data from Schedule Used - 7th Batch

Data Incorporated		Variable W (22, 100/0.298)	Average (30, 100/0.465)
MSFN Update	β (1σ) deg	0.137	0.137
(TEI + 25)	$\dot{U}$ (1σ) ft/sec	62.0	62.0
7th Batch	β	0.129	0.134
(TEI + 26)	$\dot{U}$	58.0	59.7
8th Batch	β	0.110	0.151
(TEI + 36)	$\dot{U}$	48.9	49.5
9th Batch	β	0.091	0.133
(TEI + 37)	$\dot{U}$	97.2	132
10th Batch	β	0.125	0.185
(TEI + 38.5)	$\dot{U}$	123	189
11th Batch	β	0.120	0.178
(TEI + 43)	$\dot{U}$	137	206
12th Batch	β	0.126	0.167
(TEI + 44)	$\dot{U}$	148	219
13th Batch	β	0.110	0.148
(TEI + 46.5)	$\dot{U}$	156	232
14th Batch	β	0.112	0.151
(TEI + 49.5)	$\dot{U}$	166	226
15th Batch	β	0.099	0.117
(TEI + 52)	$\dot{U}$	122	131

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 10

Communication Loss Occurs - TEI + 26 - TEI + 35
MSFN Update - TEI + 25
First Data from Schedule Used - 8th Batch

Data Incorporated		Variable W (31,300/0.264)	Average W (30, 100/0.465)
MSFN Update (TEI + 25)	β (1σ) deg	0.137	0.137
	$\dot{U}$ (1σ) ft/sec	62.0	62.0
8th Batch (TEI + 36)	β	0.102	0.103
	$\dot{U}$	49.6	49.8
9th Batch (TEI + 37)	β	0.086	0.083
	$\dot{U}$	88.0	84.8
10th Batch (TEI + 38.5)	β	0.103	0.132
	$\dot{U}$	118	123
11th Batch (TEI + 43)	β	0.103	0.143
	$\dot{U}$	130	132
12th Batch (TEI + 44)	β	0.119	0.169
	$\dot{U}$	137	147
13th Batch (TEI + 46.5)	β	0.104	0.138
	$\dot{U}$	144	153
14th Batch (TEI + 49.5)	β	0.103	0.134
	$\dot{U}$	151	160
15th Batch (TEI + 52)	β	0.092	0.114
	$\dot{U}$	117	126

Table III. Communication Loss - with Variable W and Average W (Continued)

Situation 11

Communication Loss Occurs - TEI + 35 - TEI + 36
MSFN Update - TEI + 35
First Data from Schedule Used - 8th Batch

Data Incorporated		Variable W (10, 900/0. 127)	Average (30, 100/0.465)
MSFN Update (TEI + 35)	β (1σ) deg	0.051	0.051
	$\dot{U}$ (1σ) ft/sec	20.8	20.8
8th Batch (TEI + 36)	β	0.051	0.073
	$\dot{U}$	21.4	27.3
9th Batch (TEI + 37)	β	0.045	0.054
	$\dot{U}$	24.0	66.9
10th Batch (TEI + 38.5)	β	0.054	0.125
	$\dot{U}$	29.7	118
11th Batch (TEI + 43)	β	0.052	0.138
	$\dot{U}$	31.8	128
12th Batch (TEI + 44)	β	0.062	0.168
	$\dot{U}$	34.8	144
13th Batch (TEI + 46.5)	β	0.054	0.137
	$\dot{U}$	35.6	150
14th Batch (TEI + 49.5)	β	0.048	0.133
	$\dot{U}$	43.4	158
15th Batch (TEI + 52)	β	0.049	0.113
	$\dot{U}$	83.6	126

Table IV. Effect of Execution Error in MCC-5

Data Incorporated		With Execution Error	Without Execution Error
MSFN Update (TEI + 15)	β (1σ) deg	0.213	0.166
	$\dot{U}$ (1σ) ft/sec	144	79.3
4th Batch (TEI + 16)	β	0.207	0.161
	$\dot{U}$	142	77.0
5th Batch (TEI + 20)	β	0.174	0.126
	$\dot{U}$	202	165
6th Batch (TEI + 23)	β	0.194	0.165
	$\dot{U}$	196	165
7th Batch (TEI + 26)	β	0.273	0.264
	$\dot{U}$	237	217
8th Batch (TEI + 36)	β	0.183	0.179
	$\dot{U}$	214	192
9th Batch (TEI + 37)	β	0.151	0.147
	$\dot{U}$	236	225
10th Batch (TEI + 38.5)	β	0.155	0.154
	$\dot{U}$	251	245
11th Batch (TEI + 43)	β	0.154	0.153
	$\dot{U}$	263	259
12th Batch (TEI + 44)	β	0.149	0.148
	$\dot{U}$	270	266
13th Batch (TEI + 46.5)	β	0.144	0.143
	$\dot{U}$	287	283
14th Batch (TEI + 49.5)	β	0.143	0.142
	$\dot{U}$	256	254
15th Batch (TEI + 52)	β	0.102	0.102
	$\dot{U}$	131	130

Table V. Accidental Loss of W-Matrix

Situation 1

Communication Loss Occurs - TEI + 1.5 - TEI + 10
MSFN Update - TEI
First Data from Schedule Used - 2nd Batch
First Data Following W-Matrix Loss - 3rd Batch

Data Incorporated		Variable W Used at 2nd Batch Average W Used at 3rd Batch
MSFN Update (TEI)	β (1σ) deg $\dot{U}$ (1σ) ft/sec	4.80 2681
2nd Batch (TEI + 12.5)	β $\dot{U}$	3.32 2672
Loss of W-Matrix		
3rd Batch (TEI + 13.5)	β $\dot{U}$	3.23 2597
4th Batch (TEI + 16)	β $\dot{U}$	3.01 2539
5th Batch (TEI + 20)	β $\dot{U}$	2.68 2225
6th Batch (TEI + 23)	β $\dot{U}$	2.11 1795
7th Batch (TEI + 26)	β $\dot{U}$	1.40 1563
8th Batch (TEI + 36)	β $\dot{U}$	0.676 1595
9th Batch (TEI + 37)	β $\dot{U}$	0.556 1117
10th Batch (TEI + 38.5)	β $\dot{U}$	0.391 1005
11th Batch (TEI + 43)	β $\dot{U}$	0.396 874
12th Batch (TEI + 44)	β $\dot{U}$	0.413 900
13th Batch (TEI + 46.5)	β $\dot{U}$	0.422 932
14th Batch (TEI + 49.5)	β $\dot{U}$	0.394 755
15th Batch (TEI + 52)	β $\dot{U}$	0.263 388

Table V. Accidental Loss of W-Matrix (Continued)

Situation 2

Communication Loss Occurs - TEI + 13.5 - TEI + 15
MSFN Update - TEI + 10
First Data from Schedule Used - 4th Batch
First Data Following W-Matrix Loss - 6th Batch

Data Incorporated		Average W Used at Both Reinitializations
MSFN Update (TEI + 10)	β (1σ) deg	0.152
	$\dot{U}$ (1σ) ft/sec	65.9
4th Batch (TEI + 16)	β	0.150
	$\dot{U}$	83.8
5th Batch (TEI + 20)	β	0.095
	$\dot{U}$	153
Loss of W-Matrix		
6th Batch (TEI + 23)	β	0.104
	$\dot{U}$	143
7th Batch (TEI + 26)	β	0.160
	$\dot{U}$	153
8th Batch (TEI + 36)	β	0.165
	$\dot{U}$	150
9th Batch (TEI + 37)	β	0.133
	$\dot{U}$	172
10th Batch (TEI + 38.5)	β	0.177
	$\dot{U}$	225
11th Batch (TEI + 43)	β	0.174
	$\dot{U}$	238
12th Batch (TEI + 44)	β	0.168
	$\dot{U}$	250
13th Batch (TEI + 46.5)	β	0.156
	$\dot{U}$	265
14th Batch (TEI + 49.5)	β	0.157
	$\dot{U}$	249
15th Batch (TEI + 52)	β	0.113
	$\dot{U}$	132

Table V. Accidental Loss of W-Matrix (Continued)

Situation 3

Communication Loss Occurs - TEI + 26 - TEI + 35
MSFN Update - TEI + 25
First Data from Schedule Used - 8th Batch
First Data Following W-Matrix Loss - 10th Batch

Data Incorporated		Average W Used at Both Reinitializations
MSFN Update (TEI + 25)	β (1σ) deg	0.137
	$\dot{U}$ (1σ) ft/sec	62.0
8th Batch (TEI + 36)	β	0.103
	$\dot{U}$	49.8
9th Batch (TEI + 37)	β	0.083
	$\dot{U}$	84.8
Loss of W-Matrix		
10th Batch (TEI + 38.5)	β	0.107
	$\dot{U}$	87.5
11th Batch (TEI + 43)	β	0.102
	$\dot{U}$	114
12th Batch (TEI + 44)	β	0.143
	$\dot{U}$	130
13th Batch (TEI + 46.5)	β	0.121
	$\dot{U}$	136
14th Batch (TEI + 49.5)	β	0.116
	$\dot{U}$	139
15th Batch (TEI + 52)	β	0.108
	$\dot{U}$	115

Table V. Accidental Loss of W-Matrix (Continued)

Situation 4

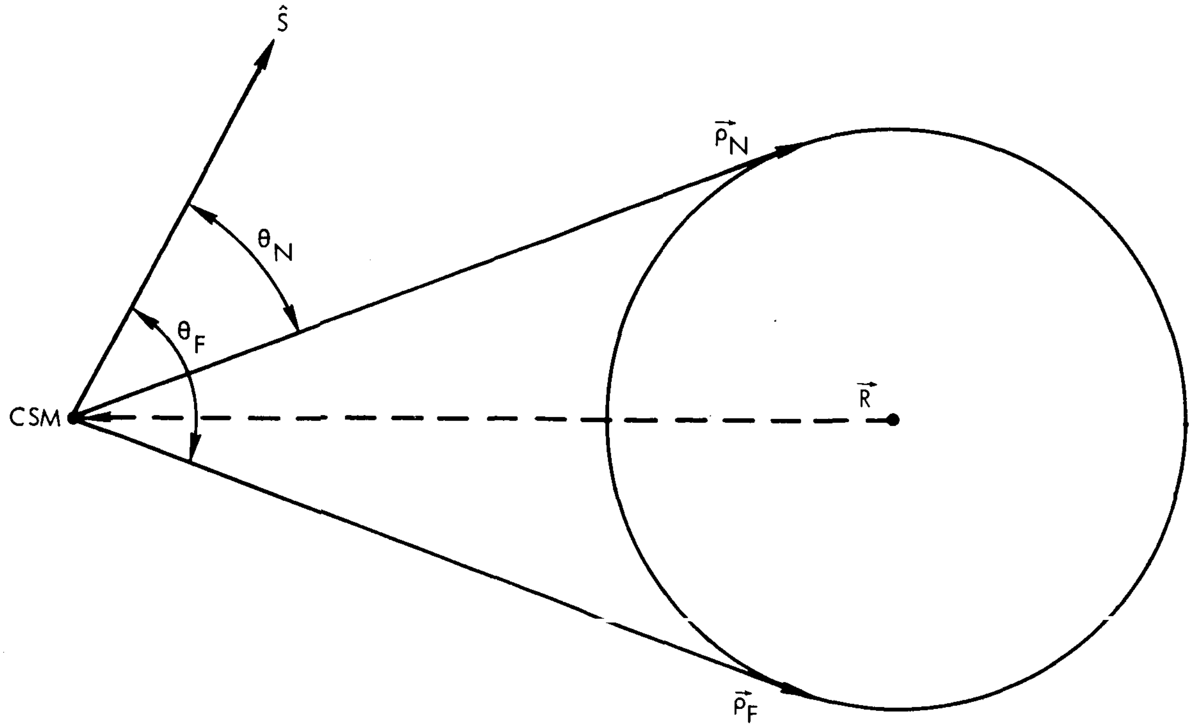
Communication Loss Occurs - TEI + 35 - TEI + 36
MSFN Update - TEI + 35
First Data from Schedule Used - 8th Batch
First Data Following W-Matrix Loss - 11th Batch

Data Incorporated		Average W Used at Both Reinitializations
MSFN Update (TEI + 35)	β (1σ) deg	0. 051
	$\dot{U}$ (1σ) ft/sec	20. 8
8th Batch (TEI + 36)	β	0. 073
	$\dot{U}$	27. 3
9th Batch (TEI + 37)	β	0. 054
	$\dot{U}$	66. 9
10th Batch (TEI + 38. 5)	β	0. 125
	$\dot{U}$	118
Loss of W Matrix		
11th Batch (TEI + 43)	β	0. 138
	$\dot{U}$	118
12th Batch (TEI + 44)	β	0. 137
	$\dot{U}$	139
13th Batch (TEI + 46. 5)	β	0. 117
	$\dot{U}$	143
14th Batch (TEI + 49. 5)	β	0. 114
	$\dot{U}$	145
15th Batch (TEI + 52)	β	0. 101
	$\dot{U}$	116

Table VI. Recommended Procedure in Case of Communication Loss

Communication Loss Time (hr from TEI)	W-Matrix To Be Input at 1st Mark	Batches of Data To Be Taken
0 - 1.5	3300/3.3	All
1.5 - 10	73,000/5.0	2nd through end of schedule
10 - 35	30,000/0.5	1st beginning after loss through end of schedule
35 - Entry*	none	none

*This assumes a MSFN update at TEI + 35 hours.



$\hat{S}$	A UNIT VECTOR IN THE STAR DIRECTION
$\vec{R}$	THE CSM POSITION VECTOR WITH RESPECT TO THE REFERENCE BODY
θ_F	THE ANGLE MEASURED BETWEEN THE STAR VECTOR AND THE VECTOR OF THE FAR HORIZON
θ_N	THE ANGLE MEASURED BETWEEN THE STAR VECTOR AND THE VECTOR TO THE NEAR HORIZON
$(\vec{\rho}_N$ OR $\vec{\rho}_F) \times \hat{S}$	THE MEASUREMENT PLANE
$\vec{\rho}_F$	FAR HORIZON VECTOR (LIES IN THE MEASUREMENT PLANE)
$\vec{\rho}_N$	NEAR HORIZON VECTOR (LIES IN THE MEASUREMENT PLANE)

Figure 1. Star Horizon Measurements

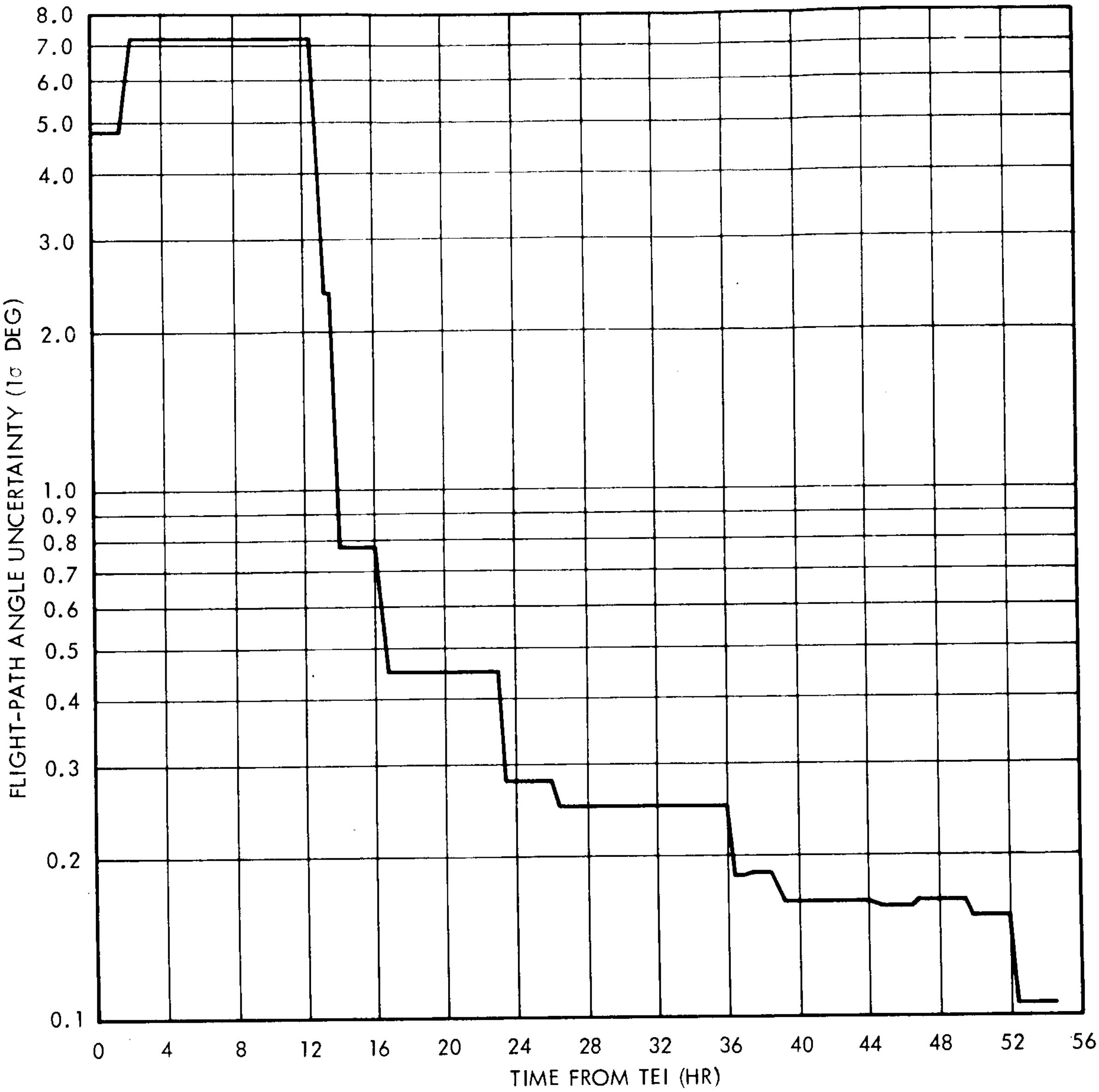


Figure 2. Reentry Flight-Path Angle Uncertainty - Full Schedule

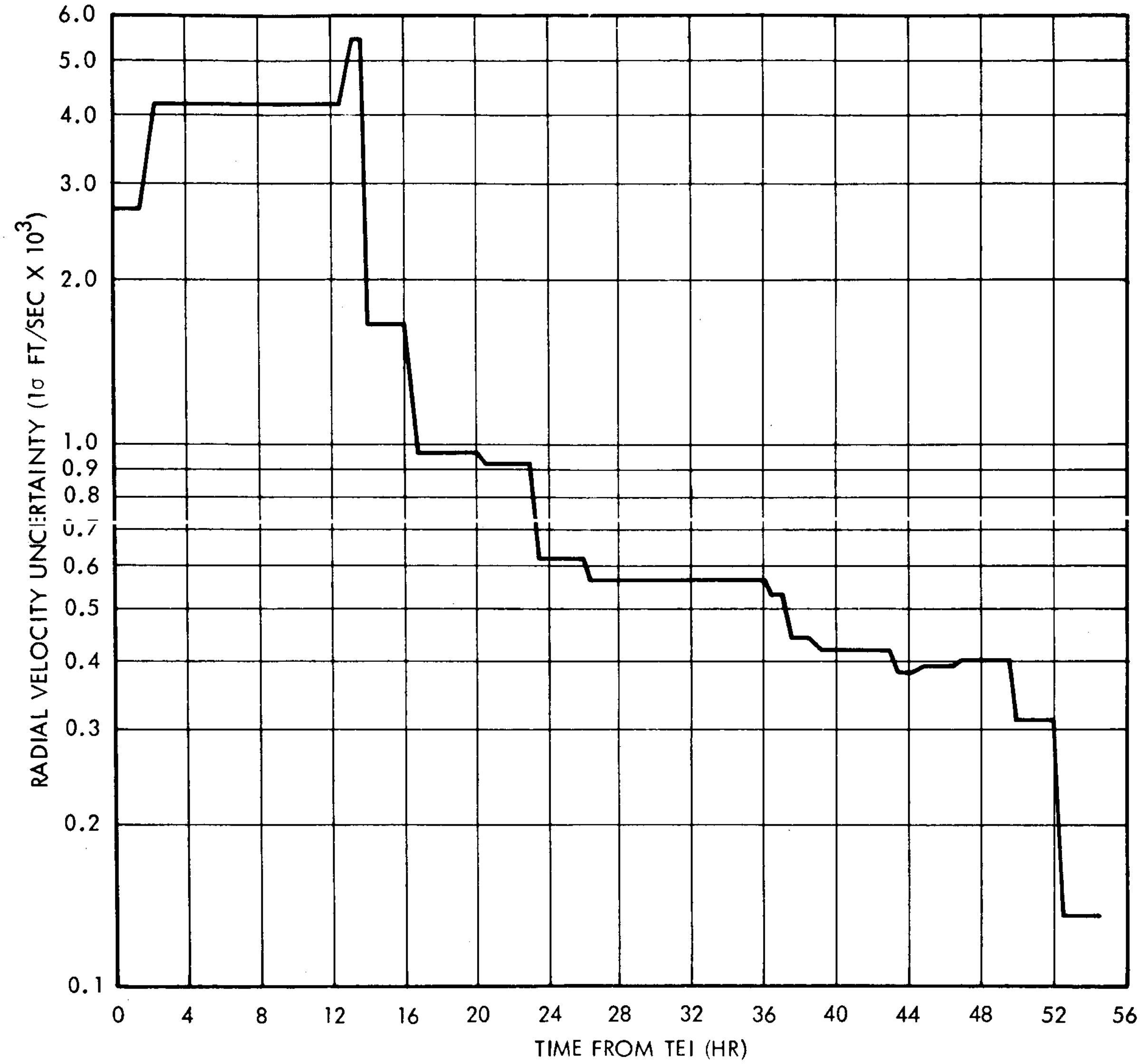


Figure 3. Reentry Radial Velocity Uncertainty - Full Schedule

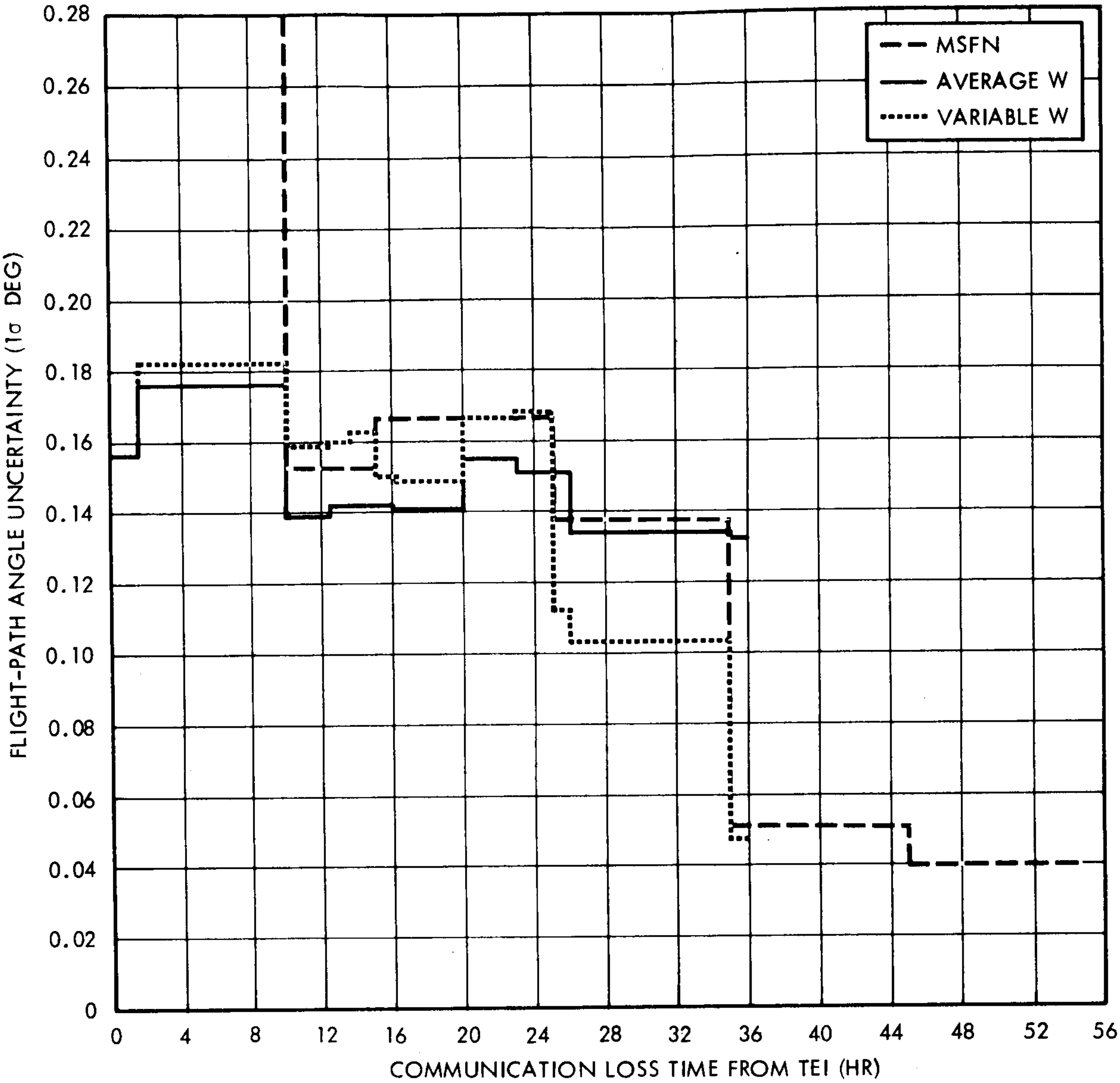


Figure 4. Reentry Flight-Path Angle Uncertainty at MCC-7

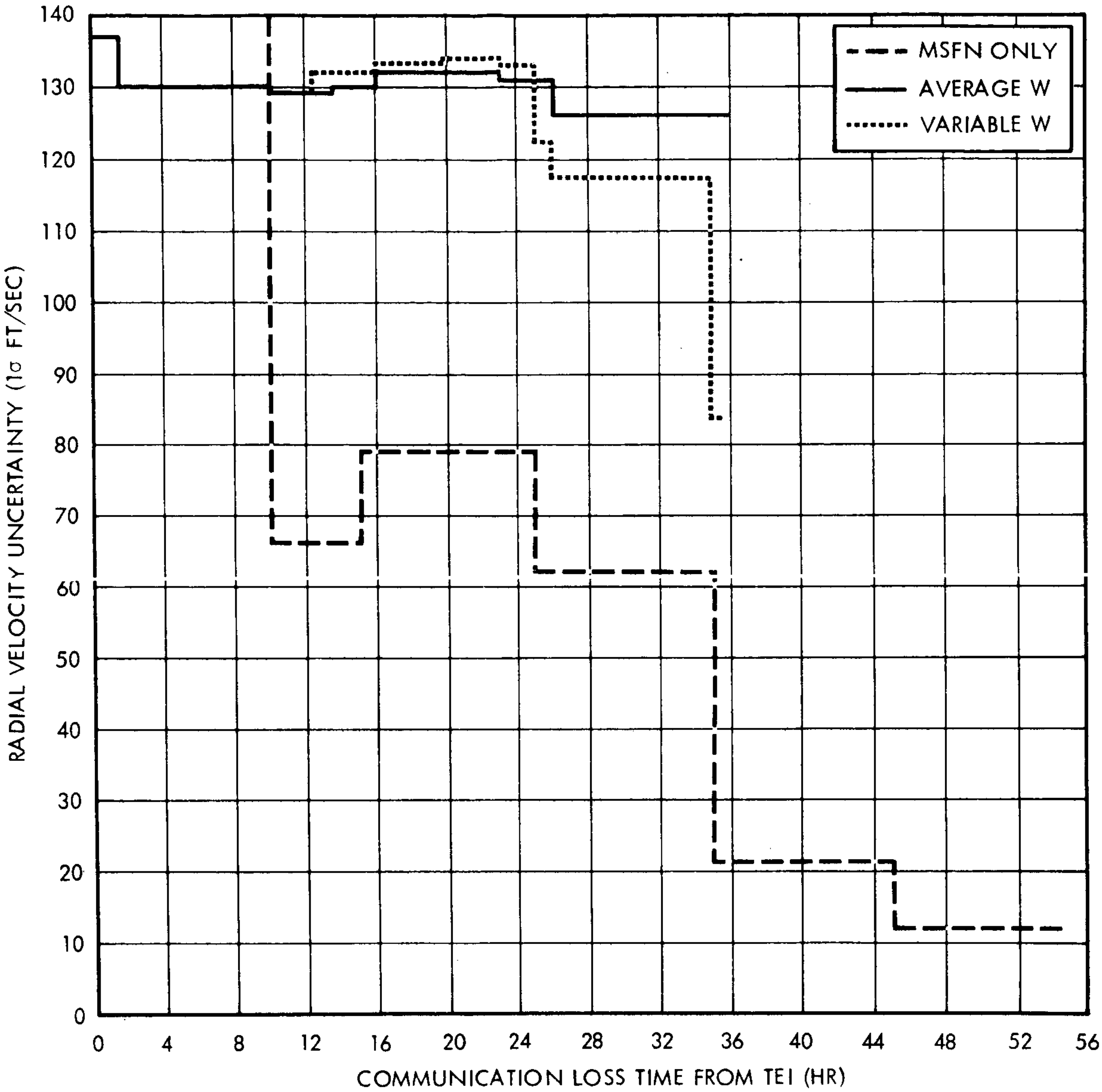


Figure 5. Radial Velocity Uncertainty at Reentry

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